SEARCHING FOR THE NEUTRINO MIXING ANGLE θ_{13} AT REACTORS [a]

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ABSTRACT

Two neutrino mixing angles have been measured, and much of the neutrino community is turning its attention to the unmeasured mixing angle, θ_{13}, whose best limit comes from the reactor neutrino experiment CHOOZ.[1)] New two detector reactor neutrino experiments are being planned, along with more ambitious accelerator experiments, to measure or further limit θ_{13}. Here I will overview how to measure θ_{13} using reactor neutrinos, mention some experiments that were considered and are not going forward, and review the current status of four projects: Double Chooz in France, Daya Bay in China, RENO in South Korea and Angra in Brazil. Finally I will mention how the neutrino observer can gauge progress in these projects two years from now as we approach the times corresponding to early estimates for new results.

1. Introduction

Since 2003, there has been a worldwide effort to plan new reactor neutrino experiments using two or more detectors to measure or further limit the only unmeasured neutrino mixing angle, θ_{13}. The best current limit on θ_{13} comes from the reactor experiment CHOOZ,[1)] which ran in the 1990's along with Palo Verde[2)] to determine if the atmospheric neutrino anomaly could be explained with θ_{12}. Here I will describe some features and the current status of reactor neutrino experiments, which I expect to be the first to improve our knowledge of θ_{13} further. The reader whose only interest is in the status of current projects can skip to Section 3.2.

In a sense, reactor neutrino $\bar{\nu}_e$ disappearance experiments are complementary to the new off-axis accelerator ν_e appearance experiments, T2K & NOνA[3,4)], whose goal is also to study θ_{13}. The magnitude of a θ_{13} signal at a new reactor neutrino experiment is affected only by the uncertainty of the value of Δm^2_{32}, which is currently bounded by $2.48 < \Delta m^2_{32} < 3.18 \times 10^{-3} eV^2/c^4$.[5,6)] On the other hand, the ability of an accelerator experiment to measure θ_{13} is also affected by the uncertainty in θ_{23}, $0.36 < \sin^2(\theta_{23}) < 0.63$[7)], and the uncertainty in the CP violating phase δ, $0 < \delta < 2\pi$. Thus a precise measurement of θ_{13} by both reactor and accelerator experiments could be used to constrain θ_{23} and/or δ. On the other hand, a failure

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to find a value for θ_{13} by the reactor experiments will have a rather negative effect on the expected physics capabilities for the accelerator experiments which are much more expensive. For example, a limit of $\sin^2(2\theta_{13}) < 0.02$, which reactor experiments could achieve before T2K or NOνA start running, would mean that the accelerator experiments, even with increases in beam power, could not measure evidence for matter effects or CP violation and would only have a narrow window to find evidence for a non-zero θ_{13}

The current limit on θ_{13} from the Chooz experiment is shown in Figure 1. The analysis was actually done for θ_{12}, but given the value of Δm^2_{21}, it serves as a valid analysis for θ_{13}. The curve shows the 90% CL allowed and prohibited values of $\sin^2(2\theta_{13})$ as a function of Δm^2_{32}. In order to compare experiments, it is common to quote a single number as the θ_{13} limit, but this requires a few assumptions. As a consequence, a large variety of numbers are quoted as the CHOOZ limit, such as $\sin^2(2\theta_{13}) < 0.10, 0.11, 0.14, 0.15, 0.20$. One cause for this is the time-dependence of the Δm^2_{32} measurement of Super-K and now MINOS. There is also no unique method of picking the value of Δm^2_{32} to use. (The union of two CL curves is not a Confidence Level.) While the "best fit" Δm^2_{32} value is often chosen, the PDG has elected to use the one sigma low value of Δm^2_{32} where the larger value of θ_{13} is achieved, and they obtain $\sin^2(2\theta_{13}) < 0.19$. Another more mundane issue which requires care is that, depending on the application, θ_{13} is often expressed in degrees, in radians, as $\sin(\theta_{13})$, $\sin^2(\theta_{13})$, $\sin^2(\theta_{\mu e})$, $\sin^2(2\theta_{13})$ and U_{e3}. The relationships between these expressions are simple, but factors of two errors are common. Finally, since comparison with the sensitivity of future accelerator experiments is often made, note that the accelerator experiments have additional ambiguities and degeneracies in interpreting a θ_{13} limit from θ_{23}, δ and the mass hierarchy.[8)]

2. The planning of a new generation of reactor neutrino experiments

The ingredients for the design of a new reactor θ_{13} experiment have been laid out in detail in the white paper, "A new reactor neutrino experiment to measure θ_{13}" prepared by an International Working Group comprised of 125 authors from 40 institutions in 9 countries[9)]. The optimum location for the far detector depends on Δm^2_{32}, and also on the experiment's ultimate exposure. Sites from 1.1 to 2.0 km have been chosen. The near detector needs to be located close to the core to measure the unoscillated spectrum. Local factors, such as reactor access and topological features modify where detectors will be placed. Important general features of reactor experiments are the effects of luminosity on the sensitivity, detector design, scintillator stability, calibration, backgrounds and systematic errors.

The neutrino oscillation sensitivity for a reactor neutrino experiment comes from measuring a smaller number of neutrinos than would be expected if $\theta_{13} = 0$, and measuring an energy distribution consistent with $\bar{\nu}_e$ disappearance due to oscillations.

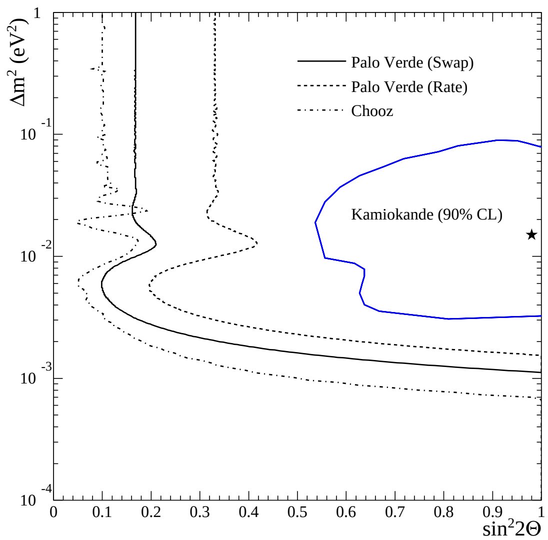

Figure 1: The CHOOZ and Palo Verde Limits on θ_{13} as a function of Δm^2_{32}.

These can be called the "rate" test and the "shape" test, but every experiment will use all available information. The effective "luminosity" for a reactor experiment can be expressed in GW-ton-years, or the product of the reactor's thermal power times the size of the detector times the length of time the detectors operate. An example of how the sensitivity of an experiment varies with luminosity is given in Figure 2. Two extreme examples, which represent straight lines on this log-log plot, are for no systematic error, and for infinite systematic error in normalization and energy calibration. In the latter case, an oscillation signature is recognized by the appropriate wiggles in an energy distribution. Such a signal would be affected by bin-to-bin systematic errors, but not by the same systematic errors which limit the "rate" test. Two other curves are drawn with possibly realistic estimates of systematic error for the next round of experiments. Vertical lines are drawn at 12 GW-ton-years, corresponding to CHOOZ, 400 GW-ton-years, which could quickly and dramatically increase the world's sensitivity, and a more ambitious project with 8000 GW-ton-years.

CHOOZ had a volume of Gd-loaded liquid scintillator, optically connected and surrounded by liquid scintillator without Gadolinium. New detector designs involve the addition of a third volume of mineral oil without scintillator, as shown in the Double Chooz design of Figure 3. An inner volume of Gd loaded scintillator serves as a well-defined fiducial volume for neutrino interactions, with a very high neutron capture cross section. A second layer of scintillator, called the "γ-catcher", measures the energy of any photons from positron annihilation or neutron capture which escape the fiducial volume, and a third volume, or "buffer", shields the active volume from

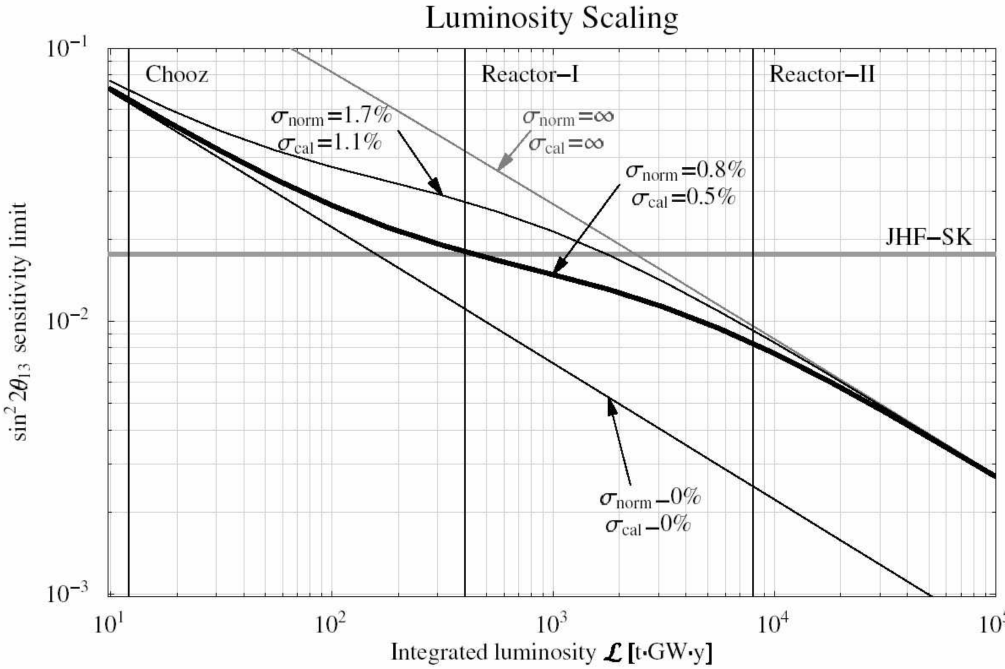

Figure 2: Luminosity scaling for a reactor experiment's sensitivity for θ_{13}. The solid curve shows what might be achieved with reasonable assumptions for systematic error.

backgrounds originating in the rock or phototubes.

The scintillator in CHOOZ showed a degradation of its transparency over time, which resulted in a decrease of the light yield. Such a degradation would be unacceptable in a new experiment, particularly if it differed between two detectors. Suspicions concentrate on possible contaminants which may have caused the Gd to come out of solution, so that clean and robust liquid handling systems will be required to maintain good optical qualities. Newly developed scintillator formulations from groups at Heidelberg[10] and Brookhaven[11] have shown that it is possible to satisfy the stability requirements for the long time periods needed.

Precise calibration will be necessary to ensure that the response of two or more detectors is identical. This will be accomplished by the introduction of radioactive sources that emit gammas, electrons, positrons and neutrons. Light flasher systems and lasers will be used to test the stability of photo-detectors. Cosmic ray muons will also be used, and particular cosmogenic nuclei, such as $^{1}2$B also can be used to provide a calibration. An important consideration is that identical calibration systems be used for all detectors. One possibility that has been proposed is to use multiple and movable detectors, in order to increase the available information regarding cross-calibration.

The neutrino signature is a coincidence between a prompt positron annihilation

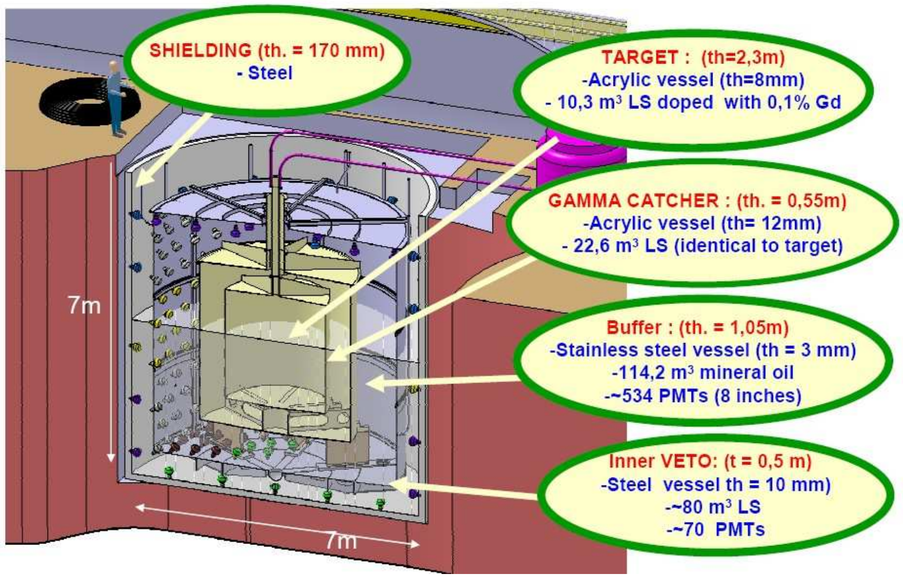

Figure 3: Plan for the Double Chooz detector(s) with three optically connected volumes: a target with 0.1% Gd, a γ-catcher with scintillator and no Gd, and a buffer with mineral oil and no scintillator.

and a delayed neutron capture with a mean life of 30 μs. There are two kinds of backgrounds: accidental ones where the two signals have different causes, and correlated backgrounds. Two important correlated backgrounds are fast neutrons, which can cause two signals separated by a typical neutron capture time, and ^{9}Li, which can be created by spallation when a muon passes through the scintillator. The danger of ^{9}Li is that it has a long decay time ($\sim$ 130 ms), and the decay leads to both a neutron and an electron, creating a signal much like a reactor neutrino. The long decay time makes it unrealistic to veto every throughgoing muon which might have been the cosmogenic source. While ^{9}Li production has been measured, its dependence on the muon energy is poorly known, so predictions of the rates at a particular depth may not be accurate. All correlated backgrounds can be reduced by putting the detectors deep enough underground so that there are large overburdens, though this has a cost in civil construction.

Finally, it is necessary to reduce the systematic errors for counting reactor neutrino events below those that were achieved by CHOOZ and Palo Verde. The use of a second detector and the definition of the fiducial volume at the target/γ-catcher interface provide large reductions in systematic errors, and the experiments have to be careful that other effects do not limit them for their planned-for statistics. A comparison of the systematic error goals for Double Chooz and Daya Bay has been tabulated by Mention et al.[19] and is presented in Table 1.

Table 1: Comparison of Systematic errors for the CHOOZ analysis and estimates of the relative and absolute errors in Double Chooz and Daya Bay, as tabulated by Mention et al. in Reference 19.

Error Description	CHOOZ	Double Chooz		Daya Bay		
					No R&D	R&D
	Absolute	Absolute	Relative	Absolute	Relative	Relative
Reactor						
Production σ	1.90 %	1.90 %		1.90 %		
Core powers	0.70 %	2.00 %		2.00 %		
Energy/fission	0.60 %	0.50 %		0.50 %		
Solid angle			0.07 %		0.08 %	0.08 %
Detector						
Detection σ	0.30 %	0.10 %		0.10 %		
Target Mass	0.30 %	0.20 %	0.20 %	0.20 %	0.20 %	0.02 %
Fiducial volume	0.20 %					
Target % H	0.80 %	0.50 %		?	0.20 %	0.10 %
Dead time	0.25 %					
Analysis						
e^+ escape	0.10 %					
e^+ identification	0.80 %	0.10 %	0.10 %			
n escape	0.10 %					
n capture % Gd	0.85 %	0.30 %	0.30 %	0.10 %	0.10 %	0.10 %
n identification	0.40 %	0.20 %	0.20 %	0.20 %	0.20 %	0.10 %
$\bar{\nu}_e$ time cut	0.40 %	0.10 %	0.10 %	0.10 %	0.10 %	0.03 %
$\bar{\nu}_e$ distance cut	0.30 %					
n multiplicity	0.50 %				0.05 %	0.05 %
Total	**2.72 %**	2.88 %	**0.44 %**	2.82 %	0.39 %	0.20 %

3. Sites for reactor experiments

3.1. Projects that were previously considered

Four reactor ν projects have received some funding and are moving forward. These four experiments, which will be described in the following sections, are Double Chooz, Daya Bay, RENO and Angra. As members of the International Working Group considered locations for new reactor experiments, a number of other possible locations were studied which have since been dropped. It is instructive to consider some of the strengths and weaknesses of sites that are not currently being pursued.

The first idea for a two-detector experiment to measure θ_{13} was KR2DET[13]. This

would have been built at the Krasnoyarsk reactor in Russia, which was originally built underground for producing weapons-grade plutonium. Two 46 ton detectors would have been 115 m and 1000 m from the reactor. Since the whole complex is underground, the 600 meters of water equivalent (m.w.e.) overburden would shield against a high rate of cosmogenic nuclei, such as ^{9}Li, and the near and far detector would have the same low backgrounds. Unfortunately, local officials were not cooperative at the prospect of an international collaboration at their formerly secret soviet city.

The reactor complex in the United States with the highest power, and the site of a former reactor neutrino experiment, is Palo Verde, in Arizona. The previous collaboration had a poor decommissioning experience and the reactor company was not approached about a new project. There was a collaboration which did an extensive site study at the Diablo Canyon reactor on the coast of California. The hills there offered an opportunity for considerable overburden for both the near and far detector. However PG&E, the reactor power company, had recently gone through a politically motivated bankruptcy, and they decided not to cooperate with the collaboration after the initial studies. The most complete proposal in the United States was put forward by a large collaboration at the Braidwood reactor, about an hour's drive from Chicago[12)]. Good cooperation with the Exelon Corporation was obtained after efforts from the Directors of Fermilab and Argonne. In Illinois, the overburden would need to be achieved by a vertical shaft rather than horizontal tunnels. Although the per-foot cost for a shaft is higher than a tunnel, the shaft height to reach a given overburden can be obtained with less digging than for the length of a typical mountain tunnel, and civil construction costs are comparable. An experiment was designed which could move two pairs of 65 ton detectors between two 180 m shafts about 1 km apart outside the reactor's security fence. After consideration by the Neutrino Scientific Assessment Group (NuSAG)[14)], the DOE decided not to fund the Braidwood experiment, presumably because it was more expensive than the alternative, which was support for U.S. participation in the Daya Bay project.

In Japan, a collaboration formed to prepare an experiment called KASKA at the Kashiwazaki-Kariwa complex south of Niigata[15)]. With seven 3.4 GW$_{th}$ nuclear power plants, it is the world's most powerful reactor complex. The plants are located in two small clusters, so two near detectors were planned. The absence of hard rock at the desired depth led to a design in which the detectors were placed in deep narrow shafts. However the economics of shafts limits their size and hence the size of the detector that could be placed in them. The collaboration developed an excellent relationship with the nuclear power company and conducted extensive boring studies to plan the shafts for 4.5 ton detectors. The Japanese funding agencies, which also support the KamLAND and Super-Kamiokande experiments, decided not to support this project.

3.2. *Double Chooz in France*

Double Chooz will use the location of the CHOOZ experiment as its site for its far detector. By avoiding civil construction costs for the far site, Double Chooz will be less expensive and will be able to get started more quickly than the alternatives. There will be a near detector location 270 m from the middle of the two reactor cores, with an overburden of about 90 m.w.e., which conservatively maintains a similar signal to background as the far detector. Engineering for a near site has been provided by the French Electricity Company, Ed.F. The final design will be completed during 2007 and the lab will be ready in 2009.

The design for the three volume Double Chooz detector was shown in Figure 3. A three volume prototype was built for the R&D stage, and the project is now entering the construction stage. Key parameters of the Double Chooz Experiment are given in Table 2. Initial tenders for the steel shielding and for the scintillator have already been issued, and the far detector will be installed and operated while the near detector lab is under construction. With just the 10 ton far detector, the CHOOZ limit on θ_{13} can be passed in a few months. When the near detector is operational, the full sensitivity can be reached quickly, as shown in Figure 4.

As the site of a former reactor neutrino experiment with extensive reactor off running, Chooz is one place where backgrounds have been measured. Accidental backgrounds in Double Chooz will be much lower than CHOOZ because sand will be replaced by 170 mm steel shielding, and because of the buffer. At the far detector, where 60 neutrinos per day will be measured, accidental backgrounds will be about 2 per day, while correlated backgrounds from fast neutrons will be an order of magnitude smaller. The estimate for ^{9}Li is 1.4 per day, based on measurements in Chooz. The near detector, which should measure 1012 neutrino events per day, will have accidental backgrounds of about 22 per day, and 1.3 per day from fast neutrons. The estimate for ^{9}Li is 9 per day. While Double Chooz will be both the cheapest experiment and the first to provide new knowledge on θ_{13}, its lower ultimate sensitivity has been used by some funding agencies to deny it the resources that could have provided that knowledge in a more timely way.

3.3. *Daya Bay in China*

The Daya Bay Complex, located near Hong Kong in Guangdong Province China, currently consists of two pairs of reactors, called Daya Bay and Ling Ao. The centers of each pair of reactors are about 1100 m apart. In addition, two more reactor cores near Ling Ao are under construction (Ling Ao II) and should be in operation by 2011, resulting in a total 17.4 GW$_{th}$ reactor power. With this geometry, two near detectors

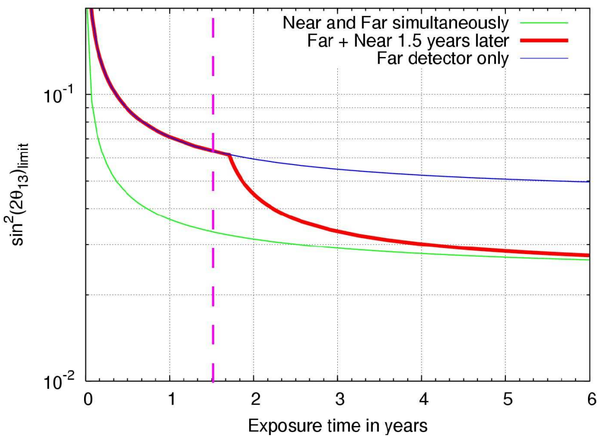

Figure 4: Expected Double Chooz θ_{13} sensitivity versus time.

Table 2: Summary of the some parameters of the proposed Double Chooz experiment.

Thermal power	4.27 GW	each of 2 cores
Electric power	1.5 GWe	each of 2 cores
$\bar{\nu}_e$ target volume	10.3 m^3	Gd loaded LS (0.1%)
γ-catcher thickness	55 cm	Gd-free LS
Buffer thickness	105 cm	nonscintillating
Total liquid volume	$\sim$237 m^3	
Number of phototubes per detector	534 8"	13% coverage
Far detector distance	1050 m	averaged
Near detector distance	280 m	averaged
Far detector overburden	300 m.w.e.	hill topology
Near detector overburden	70–80 m.w.e.	shaft
$\bar{\nu}_e$ 5 years far detector events	75,000	with a 60.5% efficiency
$\bar{\nu}_e$ 5 near detector events	789,000	with a 43.7% efficiency
Relative systematic error	0.6%	
Effective bin-to-bin error	1%	background systematics
Running time with far detector only	1–1.5 year	
Running time with far+near detector	3 years	
$\sin^2(2\theta)$ goal in 3 years	0.02–0.03	(90% CL)

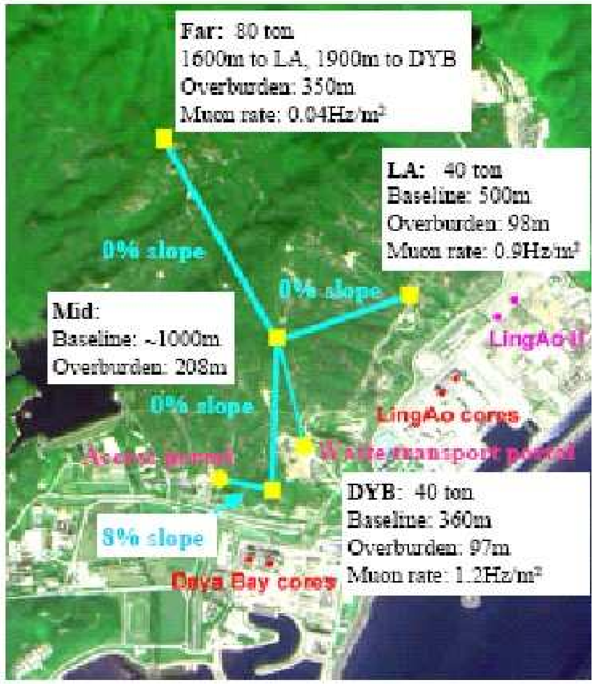

Figure 5: The layout of reactors and detectors at Daya Bay.

are needed to monitor the reactor power, as well as a far detector, as shown in Figure 5. Important factors for the near sites are the estimated muon induced backgrounds, which are a function of overburden. The near sites were optimized using a global χ^2, which takes into account backgrounds, mountain profile, detector systematics and residual reactor related systematics. A summary of distances obtained is provided in Table 3.

Table 3: Distances between reactors and planned detectors at Daya Bay.

Detectors / Reactors	DB near (m)	LA near (m)	far (m)
DB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

The cylindrical Daya Bay detector will contain three zones, with a target, γ-catcher and buffer, as described above. The 224 phototubes will be located on the sides of each 20 ton detector, with reflective surfaces at the top and bottom. The multiple detectors at each site will be used to cross-calibrate each other, and the possibility of movable detectors is being studied. In Daya Bay's baseline design, the detectors at each site are placed inside a large water buffer/water Cerenkov muon

detector. For the far hall, this is similar to a swimming pool with dimensions 16 m $\times$ 16 m $\times$ 10 m (high). In addition, water tanks of 1 m $\times$ 1 m are used as an outer muon tracker. The large depth of the Daya Bay detectors will be used to keep

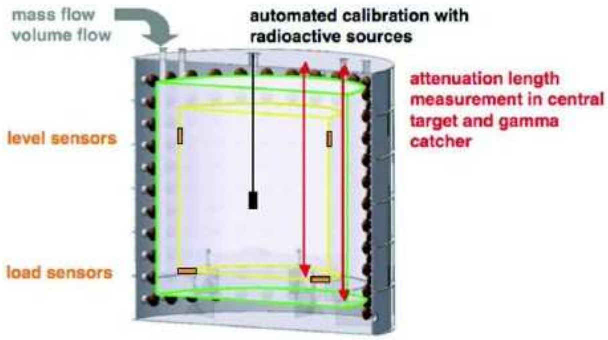

Figure 6: Design of a Daya Bay Module showing a variety of monitoring tools.

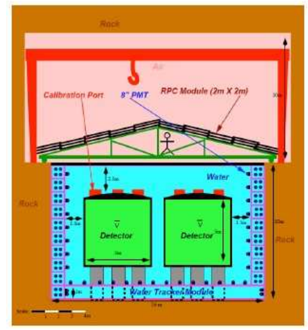

Figure 7: Daya Bay Detectors in the water buffer/Veto System

cosmogenic backgrounds at a small level. Currently, tests involving muon and neutron backgrounds are taking place with a number of detectors at the Aberdeen tunnel in Hong Kong, which has a similar overburden.

With the large reactor power and large overburden to reduce backgrounds, Daya Bay is an excellent choice for a reactor θ_{13} experiment. With support from the Chinese government and the U.S. Department of Energy, it is poised to be an excellent reactor experiment. With a baseline detector systematic error of 0.38% and a goal of 0.18%, they hope to take full advantage of the statistical uncertainty of 0.2%. Data taking with two near halls and far hall could begin in June 2010. With three years of running, Daya Bay will reach $\sin^2(2\theta_{13}) < 0.008$ or better.

3.4. RENO in South Korea

The South Korean Reactor Experiment for Neutrino Oscillation (RENO) collaboration is working on an experimental project at the YoungGwang reactor complex, which consists of six equally spaced reactors in a line on the west coast of South Korea. A schematic setup showing the topography and the proposed location of the near and far detectors is shown in Figure 8. The near detector at a distance of about 150 m would be under a 70 m high hill, and the far detector at a distance of 1.5 km would be under a 260 m high mountain.

After getting a $9M funding approved by the government of Korea, the RENO collaboration[16] has been undertaking detector design since May 2006. Various samples of liquid scintillator are under investigation with respect to the long-term stability of their optical properties. Other tests include compatibility with stainless steel and

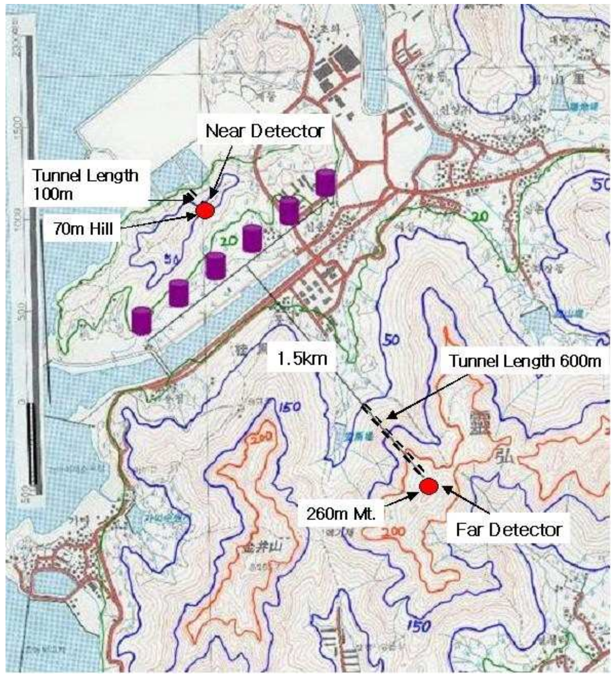

Figure 8: A topographic map of the YoungGwang site showing the proposed locations of the near and far detectors for RENO.

mylar and an acrylic cracks test. A RENO prototype contained 50 liters of Gd loaded scintillator with a 400 liter γ-catcher and a 60 cm $\times$ 100 cm stainless steel dark container. The prototype was used to do performance tests and background studies, R&D for the detector structure and phototube mounting scheme, and to establish a data analysis effort. The phototube layout in a simulation of a three-volume detector is shown in Figure 9. Each detector would have a fiducial mass of 15.4 ton using scintillator with density 0.73 gm/cm^3.

RENO has received support from the South Korean government and good cooperation from the Y.K. Power Plant Company. The expected number of $\bar{\nu}_e$'s is about 5000 per day at the near detector and 100/day at the far detector. With a systematic error near 1%, the project could reach $\sin^2(2\theta_{13}) < 0.03$ in 3 years.

3.5. Angra in Brazil

The Angra dos Reis reactor complex in Brazil, about 150 km south of Rio de Janeiro contains two reactors, Angra-I and Angra-II, which have 2 and 4 GW thermal powers and up times 83% and 94% respectively. The nearby site has high terrain consisting of granite, so both near and far detectors could have a substantial overburden. Initial designs for a θ_{13} experiment involve a near detector, 300 m from Angra-II, with 250 m.w.e. overburden, and a far detector, under the peak of a mountain called "Morro de Frade", which would provide 2000 m.w.e. at a distance of 1.5

Figure 9: The phototube configuration in the RENO GEANT simulation.

km. Thoughts are to build a 50 ton near detector and a 500 ton far detector, and concentrate on reducing any bin-to-bin systematic errors. The 1000 ton KamLAND detector is a proof that large reactor neutrino detectors are possible. Unlike KamLAND but like the other new θ_{13} projects, the Angra collaboration plans to build a three-volume detector. For such a large detector, phototube costs scale as $V^{2/3}$. A statistical precision of $\sin^2(2\theta_{13}) < 0.006$ could be obtained in three years.

The Angra experiment was originally conceived as a large θ_{13} detector under a considerable overburden together with a single reactor in order to obtain an large luminosity but still have substantial reactor off running. A funding request to the Brazilian Minister of Science and Technology in 2006 was approved for initial stages of the project. The experiment will be a long term project which will take advantage of lessons learned at Double Chooz, Daya Bay and RENO. In the meantime, smaller detectors are being constructed with possible applications toward the monitoring of reactor operations. The collaboration is establishing a formal agreement with Eletronuclear for permanent access to the site. They are already authorized to place one ton of Gd-loaded scintillator provided by LVD near to the reactor for muon background measurements. Other tests have measured noise and singles rate in the vicinity of the proposed detectors.

The next stage is a very near detector with three volumes of scintillator and a muon to be placed between 50 and 100 m from the core. The current design is a cylinder, 1.3 m high and with a 0.5 m radius for the target, 1.9 m high and 0.8 m radius for the γ-catcher, and 3.1 m high with a 1.4 m radius for the buffer.

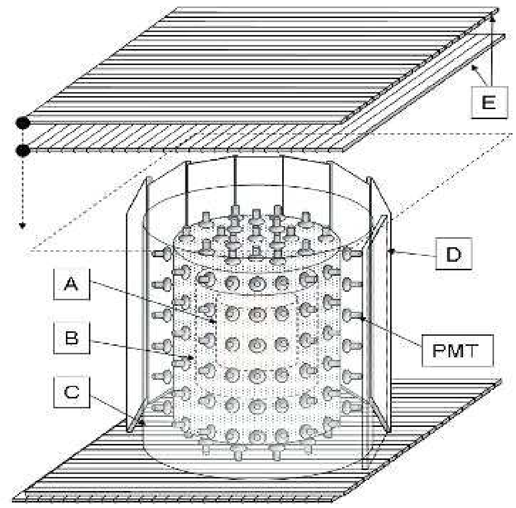

Figure 10: Design for the Angra Very Near Detector with A) target of liquid scintillator and Gd, B) γ-catcher of scintillator, C)Buffer of mineral oil and D,E) Muon veto system of plastic scintillator panels.

3.6. A comparison of current reactor ν projects

Two summaries of some features of the four current projects are given in Tables 4 and 5. These tables were prepared with input from each collaboration's management in October 2005[17] and may not be up to date. In any case, the exact size and location of the detectors is subject to further modifications in design, and the "optimistic start dates" need to be taken with a huge clump of salt.

Table 4: Comparison of Detectors for four reactor ν projects.

Project	Power (P)	$< P >$	Location	Detectors
	GW_{th}	GW_{th}		km/ton/m.w.e.
Angra	6.0	5.3	Brazil	0.05/1/20 0.3/50/250 1.5/500/2000
RENO	17.3	16.4	Korea	0.15/20/230 1.5/20/675
Daya Bay	11.6 (17.4 after 2010)	9.9 (14.8 after 2010)	China	0.36/40/260 0.50/40/260 1.75/[40x2]/910
Double Chooz	8.7	7.4	France	0.27/10.2/90 1.067/10.2/300

Table 5: Comparison of Physics for reactor experiments. (* For Daya Bay after 2010)

Project	Start Date optimistic	GW-t-yr (yr)	90% CL $\sin^2(2\theta_{13})$	for Δm^2_{32} ($10^{-3}eV^2$)	efficiences	Far event rate
Angra	2013(full)	3900(1) 9000(3) 15000(5)	0.0070 0.0060 0.0055	 2.5 2.5	0.8×0.9	350,000/yr
RENO	2009	340(1)	0.03	2.0	0.8	18,000/yr
Daya Bay	2009	3700(3)	0.008	2.5	0.75×0.83	70,000/yr 110,000/yr*
Double Chooz	2007(far) 2008(near)	29(1) 29(1+1) 80(1+3)	0.08 0.04 0.025	2.5	0.8×0.9	15,000/yr

A comparison of the philosophy of the new reactor projects can be discerned by a critical examination of Figure 2. The thick curve shows the evolution of θ_{13} sensitivity with reactor luminosity for a particular set of assumptions about the detector locations, Δm^2_{32} and systematic error. That curve showed a transition from near the sensitivity of the rate-only test to near the sensitivity of the shape-only test between 200 and 2000 GW-ton-year. The Double Chooz and RENO projects aim to quickly improve the limit by reaching the "transition" near 200 GW-ton-year. Daya Bay has adopted a goal to work hard to reduce systematic errors below the assumptions of Figure 2. It will reach $\sin^2(2\theta_{13}) \sim 0.01$ with 2000 -ton-year, perhaps by using movable detectors. Angra's strategy is to build a much larger far detector with $> 10,000$ -ton-year to make it less sensitive to systematic error. Depending, of course, on Δm^2_{32}, it is reasonable for the field to have a sensitivity goal of $\sin^2(2\theta_{13}) \sim 0.01$, as might be achievable with the Daya Bay or Angra experiments. However, as can be seen for Figure 2, the luminosity requirement for 0.01 is 70 times larger than for 0.03, following the thick curve. In that sense, a 0.01 experiment is 70 times harder than an 0.03 experiment, and the earlier and less expensive Double Chooz and RENO projects can be valuable steps on the learning curve for a successful 0.01 experiment.

It would be desirable to compare the real schedules of these four projects. All four projects have some funding, though not necessarily enough to reach their design goals (yet). Even though it is the cheapest experiment, Double Chooz' schedule is limited only by funding. The other four projects, which will require considerably more civil construction, also have schedules that are probably limited both by funding and by technical considerations.

4. The near future

The earliest results from reactor experiments may be three years or more away. However, at the next Neutrino Telescopes meeting in 2009, observers will be able to gauge progress by paying attention to the following subjects:

- Updated estimates of GW-ton-year as the final detector design and efficiencies are completed,
- Liquid scintillator production and stability and attenuation length studies using large amounts of liquid scintillator,
- Civil construction issues and, in particular, experience with costs and schedules,
- Improved estimates of the background for cosmogenic sources such as ^9Li, (It may be possible to achieve an improved understanding of the possible production mechanisms for cosmogenic sources. In any case, each experiment should carefully estimate the range of uncertainty of their background estimates, the impact that uncertainty would have on the θ_{13} sensitivity, and quantitative methods for measurements that will lead to a reduction of the uncertainty when data taking is underway.)
- Calibration system development and the results of relative calibration measurements between two or more detectors.
- Progress in the implementation of movable detectors as a calibration technique, and evidence as to whether this is a reliable method, given the progress or absence of changes when the detectors are moved.

5. The longer term

Due to the importance of θ_{13} for CP violation and the mass hierarchy, a potential long-term program of reactor neutrino measurements lies ahead of us. Results from Double Chooz, Daya Bay, RENO, and later Angra, will be used to determine the value of upgrades, additional detectors, and new projects. An important factor will be whether the goal becomes further limits on a small value of θ_{13}, or more precise measurements of a non-zero value. Statistical precision better than $\delta(\sin^2(2\theta_{13})) < 0.01$ can be imagined, but experience with systematic errors and backgrounds must be weighed along with the capabilities and needs of accelerator experiments. Ideas already exist for more ambitious reactor experiments to study θ_{13} further, as well as θ_{12}. Some examples are Triple Chooz[20], R2D2[21] and Hano Hano[22]. If such

projects become reality, they will certainly be based on lessons not yet learned by Double Chooz, Daya Bay, RENO and Angra.

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7. References

1) M. Apollonio et al., Eur. Phys. J. C27 (2003) 331-374.
2) F. Boehm et al., Phys. Rev. Lett. 84, 3764(2000).
3) Tokai to Kamiokande (T2K) Letter of intent, "Neutrino Oscillation Experiment at JHF", Y. Hayato et al., January 21, 2003; Available at http://neutrino.kek.jp/jhfnu/loi/loi_JHFcor.pdf.
4) Neutrino Oscillation ν_e Appearance (NOνA) Proposal, "Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \rightarrow \nu_e$ Oscillations in the NuMI Beamline, D.S. Ayres et al., March 21, 2005; Available at http://nova-docdb.fnal.gov/0005/000593/001/NOvA_P929_March21_2005.pdf.
5) P. Adamson et al., Phys. Rev. D73 (2006) 072002.
6) Patricia Vahle for the MINOS collaboration, "The Status of MINOS in the Second Year of Beam Running", these proceedings.
7) W.-M.-Yao et al., J. Phys. G: Nucl. Part. Phys. 33 (2006), 1; also known as the Review of Particle Physics from the Particle Data Group.
8) P. Huber et al., Phys.Rev. D70 (2004) 073014.
9) K. Anderson et al., "A New Nuclear Reactor Neutrino Experiment to Measure θ_{13}", Also known as the reactor neutrino White Paper, Available at hep-ex/0402041.
10) Double Chooz Proposal, F. Ardellier et al., "Double Chooz: A Search for the Neutrino Mixing Angle θ_{13}", available at hep-ex/0405032.
11) Daya Bay Proposal, "A Precision Measurement of the Neutrino Mixing Angle θ_{13} Using Reactor Antineutrinos at Daya Bay.", December 1, 2006, available at hep-ex/0701029.
12) The Braidwood Collaboration, "Braidwood Project Description", available at http://mwtheta13.uchicago.edu/project_web.ps
13) V. Martemyanov et al., "The KR2DET project: Search for mass-3 state contribution to $|U_{e3}|^2$ to the electron neutrino using a one reactor - two detector oscillation experiment at Krasnoyarsk underground site",

Phys.Atom.Nucl. 66 (2003) 1934-1939; Yad.Fiz. 66 (2003) 1982-1987; Available at arXiv:hep-ex/0211070.
14) Neutrino Scientific Assessment Group, "Recommendations to the Department of Energy and the National Science Foundation on a U.S. Program of Reactor- and Accelerator-based Neutrino Oscillation Experiments", February 28, 2006; available at http://www.science.doe.gov/hep/NuSAG2ndRptFeb2006.pdf.
15) KASKA Letter of Intent, M. Aoki et al., "Letter of Intent for KASKA: High Accuracy Neutrino Oscillation Measurements with $\bar{\nu}_e$'s from Kashiwazaki-Kariwa Nuclear Power Station", 11 July 2006, available at hep-ex/0607013.
16) See http://neutrino.snu.ac.kr/RENO/
17) Private communication with spokespersons of Angra, Daya Bay, Double Chooz and RENO during September 2005 for the 8th ICFA Seminar on "Future Perspectives in High Energy Physics", Kyungpook National University, Daegu South Korea, October 2005. http://chep.knu.ac.kr/ICFA-Seminar/.
18) J.C. Anjos et al., Brazilian Journal of Physics, 36 4A(2006)
19) G. Mention et al., "A unified analysis of the reactor neutrino program toward the measurement of the θ_{13} mixing angle.", hep-ex/0704.0498/.
20) P. Huber et al., JHEP 05 (2006) 072.
21) P. Huber et al., JHEP 0502 (2005) 029.
22) J. Learned, "Hano Hano", these proceedings.